Control Engineering Practice 17 (2009) 1432–1439

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Motion planning for experimental air path control of a variable-valve-timing spark ignition engine

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ARTICLE INFO

Article history:
Received 15 May 2008
Accepted 13 October 2008
Available online 1 December 2008

Keywords:
Engine control
Spark ignition engines
Time-varying systems
Nonlinear observers

ABSTRACT

Air path control of a spark ignition engine without an EGR loop, equipped with variable-valve-timing (VVT) actuators, is addressed in this paper. VVT devices are used to produce internal exhaust gas recirculation, providing beneficial effects in terms of fuel consumption and pollutant emissions reduction. However, VVT actuators affect the fresh air charge in the cylinders. This has an impact on the torque output (leading to driveability problems) and on the fuel/air ratio (FAR) (leading to pollution peaks). To compensate for these undesirable effects, a new approach is proposed. Supportive experimental results show the relevance of this approach.

1. Introduction

1.1. Motivation

Lately, variable-valve-timing (VVT) actuators have been used in spark ignition (SI) engines to exploit all of the possibilities of direct injection and turbocharging. This approach is of particular interest in the context of downsizing (reduction of the engine size), which has appeared as a major solution to the problem of reducing fuel consumption (see Lecointe & Monnier, 2003). In the present study, the engine under consideration was not equipped with any exhaust gas recirculation (EGR) capability.

VVT systems use electrohydraulic mechanisms which rotate the camshaft to modify the breathing of the engine. A beneficial effect is a reduction of the pumping losses. For a given engine torque output, an increase in the valve overlap (the number of crankshaft angle degrees during which both valves are opened) implies an increase in the intake manifold pressure (see Fig. 1a). The negative work necessary to suck air into the cylinder is then reduced. VVT systems also allow internal EGR, leading to reduction in emissions of nitrogen oxides (NO_x) (Shaver, Roelle, & Christian Gerdes, 2006) (see Fig. 1b).

1.2. Control problem

One basic task in engine control is managing the torque output of the engine according to the driver's requirements, while limiting pollutant emissions. Torque control is achieved by managing the in-cylinder air mass, while keeping the fuel/air ratio (FAR) to the stoichiometric value in order to maximize the efficiency of the three-way catalyst and thus minimize the pollutants (CO, hydrocarbons, and NO_x) created by combustion (Guzzella & Onder, 2004).

In conventional SI engines, a reference in-cylinder air mass is computed directly from the intake manifold pressure through a quasi-static relation depending on the volumetric efficiency (see Heywood, 1988). Controlling the air is achieved by modulation of the intake pressure through the intake throttle (see Khiar et al., 2007 for example). In parallel, the FAR management consists classically of a PID controller using a FAR measurement (given by an oxygen sensor situated at the engine exhaust), which is complemented by a feedforward control law to limit FAR fluctuations during torque transients (Grizzle, Cook, & Milam, 1994). The FAR controller acts upon the reference fuel mass which is sent to the injection system. The feedforward control law is designed according to a prediction of the air mass in the cylinders (Chevalier, Vigild, & Hendricks, 2000).

In SI engines equipped with VVT actuators, the in-cylinder air mass depends also on the positions of the VVT actuators. Thus, VVT has an impact on the volumetric efficiency of the aspiration from the intake manifold into the cylinders (see Heywood, 1988). Its influence can be modeled (see Colin, Chamaillard, Bloch, & Corde, 2007; Leroy, Chauvin, Le Berr, Duparchy, & Alix, 2008;

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doi:10.1016/j.conengprac.2008.10.010

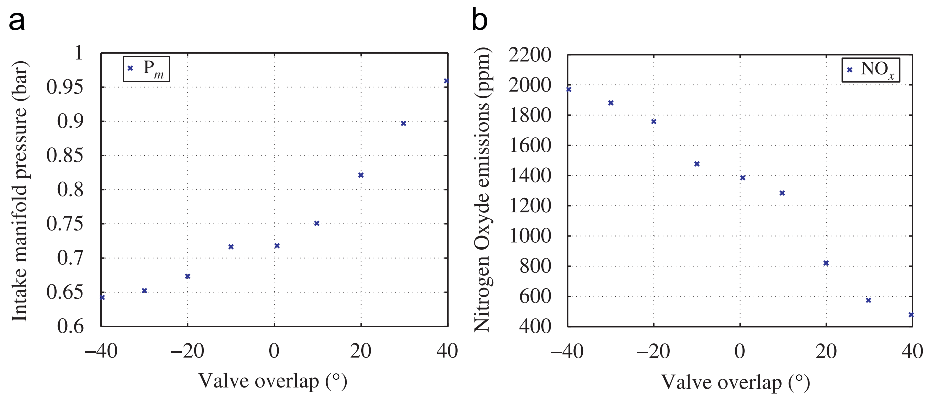

Fig. 1. Experimental (a) intake manifold pressure and (b) NO_x measurements as a function of the valve overlap at constant indicated mean effective pressure (5 bar) and constant engine speed (2000 rpm).

Stefanopoulou, Cook, Grizzle, & Freudenberg, 1998, for example), but errors cannot be avoided, leading to in-cylinder prediction errors, which unavoidably propagate, through feedforward terms, into the FAR management system. This issue generates pollution peaks and results in poor driveability.

1.3. Proposed control strategy

A simple alternative solution is proposed here. Focusing on the in-cylinder air mass control problem only, two types of modeling errors are compensated with an improved control strategy. The intake dynamics is modeled as a first-order system, using the above-mentioned volumetric efficiency related to the VVT actuators, and one consider two biases. One of these represents errors in the experimentally determined look-up table of the throttle effective area. The other accounts for errors in the volumetric-efficiency law. Provided that these biases are known, one obtains a one-dimensional actuated dynamics, for which the motion-planning and trajectory-tracking problems are already solved. From a more realistic standpoint, a compensation of these two biases can be obtained by use of an integral term and an observer. In parallel, the FAR management system simply assumes that the reference signal for the in-cylinder air mass is tracked. Experimental results prove the relevance of this approach.

This paper is organized as follows. In Section 2, the reference model for the intake manifold is presented. This model consists of mass balance and aspirated-flow equations. The control problem is also presented in this section. In Section 3, the control strategy is outlined. The first part considers generation of the motion-planning trajectory of the intake manifold pressure from a torque set point. Then, feedforward and feedback control laws are presented. In Section 4, experimental results obtained on a test bench are shown.

2. Control problem and system modeling

2.1. Air path modeling

In numerous references found in the literature (e.g. Chevalier, Müller, & Hendricks, 2000), mean-value engine modeling approaches are presented as a reliable and efficient way to represent engine dynamics. Because the complexity of the model impacts on the design of the control system, however, a simplified model of the intake manifold is proposed here.

2.1.1. Balance in the intake manifold

Notation is provided after Conclusions. Consider the air path of an SI engine equipped with VVT actuators as depicted in Fig. 2. In this configuration, i.e. with internal EGR, the air path has a very simple structure. It can be modeled by an intake manifold which has an inlet flow (controlled by the throttle) and an outlet flow (impacted on by the VVT actuators). The intake manifold is considered to have a constant volume, in which the thermodynamic state (pressure, temperature, and composition) is assumed to be spatially homogeneous. Also, time variations of the temperature are neglected in this volume (following Andersson & Eriksson, 2001; Guzzella & Onder, 2004), i.e. $\dot{T}_m = 0$. Under these assumptions, a mass balance in the intake manifold gives

$$\dot{P}_m = \alpha_m(\dot{m}_{at} - \dot{m}_{asp}) \tag{1}$$

where $\alpha_m \triangleq RT_m/V_m$. Both P_m and T_m are measured by sensors located in the intake manifold. $\dot{m}_{at}$ is the intake mass air flow. In this study, one neglect the intercooler volume. Then, $\dot{m}_{at}$ can be well approximated by the mass air flow measured at the intake, $\dot{m}_{MAF}$. Correspondingly, $\dot{m}_{asp}$ is the mass air flow aspirated into the cylinders.

The intake mass air flow, $\dot{m}_{at}$, can be modeled in the form

$$\dot{m}_{at} = Area_{th} \cdot f(P_m) \tag{2}$$

where $Area_{th}$ is the effective opening area of the throttle. The mass flow rate per unit area, $f(P_m)$, is given in Heywood (1988), in the form

$$f(P_m) = \frac{P_{dc}}{\sqrt{RT_m}} \begin{cases} \left(\frac{P_m}{P_{dc}}\right)^{1/\gamma} \sqrt{\frac{2\gamma}{\gamma-1}\left(1-\left(\frac{P_m}{P_{dc}}\right)^{(\gamma-1)/\gamma}\right)} & \text{if } \left(\frac{P_m}{P_{dc}}\right) > 0.528 \\ \sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} & \text{otherwise} \end{cases} \tag{3}$$

where P_{dc} is the measured downstream compressor pressure, and γ is the ratio of specific heat capacities in the intake manifold.

The effective area of the throttle is usually modeled with a polynomial function of the angular position of the actuator, i.e. $Area_{th} = \mathscr{A}(\theta_{th})$. Fig. 3 presents the modeled and experimental opening areas of the throttle as a function of the angular position of the actuator.

As the model (2) is not perfect, one can add a modeling error term ε_{th}, leading to the following relation:

$$\dot{m}_{at} = \mathscr{A}(\theta_{th})f(P_m) + \varepsilon_{th} \tag{4}$$